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DISCLAIMER

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SIMULATION OF REGIONAL EXPLOSION S-PHASES (SIRES) PROJECT

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ABSTRACT

Generation of S-waves from explosion sources continues to be an intriguing area of seismological research. Empirical studies document a general decrease in regional S-phase amplitudes (compared to P-phases) for explosions sources. Although decreased S-phase amplitude for explosive (compressional) sources is intuitive, a comprehensive physical understanding of the many mechanisms that contribute to S-phase excitation does not currently exist. Despite the success of many regional discriminant and magnitude methods that rely on decreased S-phase amplitude for explosion sources, instances remain where explosions produce anomalous S-phases amplitudes that confound regional methods.

Scattering of the Rg phase is forwarded in several studies as an important mechanism for the generation of explosion S-waves. In this study we construct a 3-dimensional model of the Nevada Test Site (NTS) and the surrounding region. Extensive databases of geologic information, including existing 3-dimensional models developed under past and ongoing NTS programs, are used in the construction of a local model. The detailed local model is merged into a regional model that extends several hundred kilometers from the NTS. In addition to deterministic geologic structure and topography we introduce stochastic variability along geologic contacts and within geologic units. Model roughness made possible by the stochastic perturbations enhances scattering, allowing realistic simulation of the local and regional wavefield. In this phase of the project we report on version 1 of the NTS model and on preliminary validation tests. Validation simulations use e3d, a fully elastic, finite difference computer code. This code allows us to introduce 3D topographic effects, as well as 3D geologic variability. Simulations are compared to recordings of the 1993 NPE experiment. The validation data set consists of local and regional distance seismograms and provides a rigorous test of the distance and time evolution of the wavefield.

OBJECTIVE

Regional monitoring relies heavily on S-phases. Discriminants commonly use P- and S-wave amplitude ratios (Pomeroy et al., 1982; Walter et al., 1995). Widely used methods of determining magnitude make use of Lg and Lg coda amplitudes (e.g. Nuttli, 1986; Mayeda and Walter, 1996; Patton, 2001), and regional S-phases often add important arrival-time observations to limited, small-magnitude datasets used for location (PNE volume, 1994, Mayeda and Walter, 1996, Myers et al. 1999).

Most investigators agree that appreciable energy from the explosions is converted to S-waves near the source, but the dominant P-to-S transfer mechanism is not agreed upon. Several physically reasonable transfer mechanisms are proposed, including P-to-S conversion at the free surface, spall, scattering of short-period surface waves, tectonic release, and rock-damage (e.g. Vogfjord, 1997; Day and Mclaughlin, 1991; Gupta et al., 1992; Wallace et al., 1985; Johnson and Sammis, 2001). Each mechanism fits a subset of observations, and each mechanism, with the exception of surface-wave scattering, is understood from first principles. Currently the Rg-to-S mechanism is represented by an empirical transfer function (e.g. Gupta et al., 1992; Patton, 2001). Notwithstanding the ultimate goal of deriving the transfer function from first principles, application of the empirical transfer function would be bolstered if the Rg-to-S mechanism could be simulated. This study aims to conduct full simulations in realistic geology of the explosion source. The simulations focus near the source to see if Rg is converted to higher-mode S-wave. If Rg-to-S is observed in local simulations, we further characterized the propagation of S-waves to regional distance.

RESEARCH ACCOMPLISHED

NPE Case Study

We fashion seismic simulations around the 1993 Non-Proliferation Experiment (NPE) (see reference in Denny and Stull, 1994). The NPE was a chemical explosion with nominal yield of 1 kiloton. Knowledge of the source location, origin time, emplacement conditions, and near source geology are unparalleled, providing an excellent data set for modeling.

Geological Modeling

One of this project's goals is to produce a realistic model that can be used in seismic simulations. Because of our focus on the generation of S-waves near the source, we have built a highly accurate, 20km-20km-8km model that is centered on the NPE shot. This local model is imbedded in a 3-dimensional, lithospheric-scale model that extends several hundred kilometers from the NPE. Throughout the model we implement stochastic perturbations of the geologic structure. These perturbations introduce heterogeneity to parts of the model where resolution is limited.

Local Model

A detailed geologic model near the source is needed to produce a realistic simulation of Rg scattering. The local model is based on surface mapping and an extensive borehole database at LLNL (Figure 1). The detailed model extends 10 km from the NPE shot and to a depth of 8 km. A digital elevation model (DEM) with 10-meter resolution is used in the local model, and the following stratigraphic units are specified: Quaternary alluvium, welded tuff, un-welded tuff, Tertiary volcanics, Mesozoic intrusives, Paleozoic sedimentary and metasedimentary rocks, and upper-crustal crystalline rocks. Each of these stratagraphic units has distinct seismic properties and significant scattering of seismic waves can occur at the contacts between these units. As an example, we show the top of the Paleozoic (Figure 1), which is constrained by numerous borehole data points. Two other examples are the intrusive granites (Gold Meadows stock and Climax stock; green in Figure 1), which are locally exposed at the surface, penetrated by several boreholes and further constrained by gravity modeling (Healey and Miller, 1963; USGS OFR, 1983).

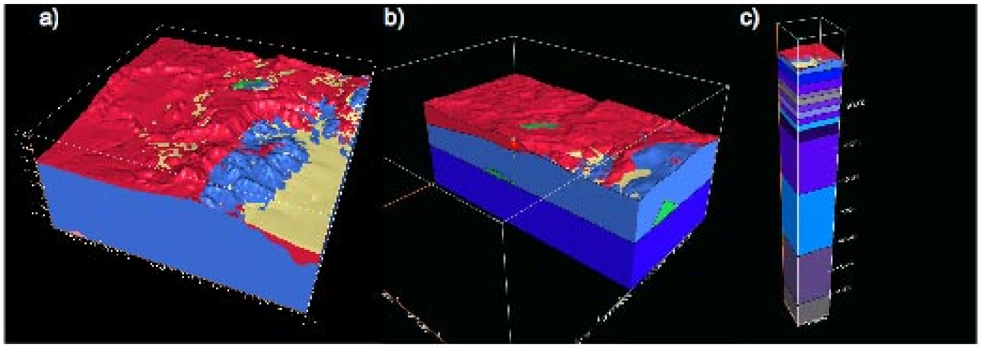

Figure 1. Local model around NPE shot determined from detailed geologic and geophysical studies. a) The entire local model. b) Cross section through the NPE shot. c) Local model merged into a lithospheric velocity stack.

Regional Model
The regional model is based on a slightly modified version of the 1-dimensional Patton and Taylor (1984) model. The Patton and Taylor model is constrained by surface-wave modeling, giving us confidence that our model will predict longer-period seismic data. A minor adjustment in Moho depth (Myers et al. 2003) improves prediction of regional body phase arrival times. We add topography, basin structures, variable Moho depth, and lateral velocity variations to the 1-dimensional model. Figure 2 is an example of the geologic information that we have compiled to constrain the upper crust of the regional model.

Our seismic simulations suggest that topography significantly effects regional wave propagation. We have compiled several DEMs that, taken together, cover our modeling area. Significant effort was required to merge these models into a seamless DEM with 80m resolution (Figure 2). The high resolution DEM enables use to push simulations to higher frequency, with confidence that topographic effects are adequately modeled.

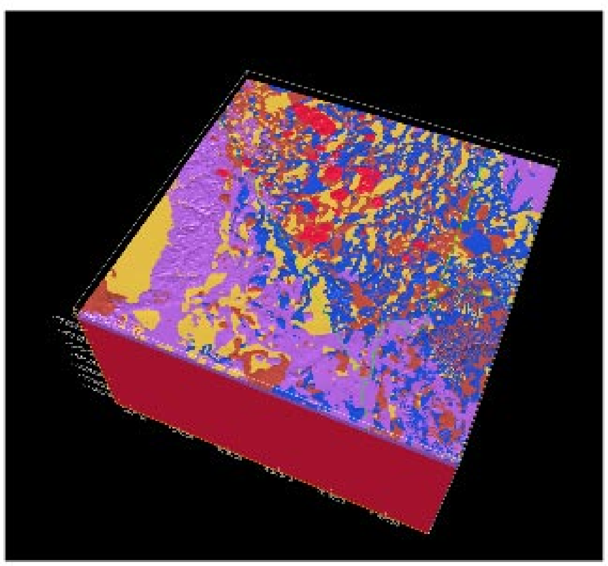

Figure2. Compilation of geologic information spanning the states of Nevada, California, Utah, and Arizona. The geologic information is used to constrain the upper crust for our geophysical model. In this preliminary compilation some of the geologic features are not properly merged, causing crystalline units to appear at the surface instead of basins. Reconciliation of these details is required before model finalization.

Inclusion of sedimentary basins in the model is needed if synthetics are to match the coda durations of Pg, Lg, and longer-period surface waves (Preston et al., 2004). Blakely et al. (1999) produced a detailed basement map in the Death Valley region from gravity data, and found that large basins may contain numerous hidden sub-basins of varying depth and extent. We adopt Blakely's basin structure for the southwest portion of our model, and we use a simplified methodology to characterize basins elsewhere. Our simple characterization utilizes geologic mapping (Figure 2), mapped faults to bound basin edges, and the relative variations in local gravity data as a proxy for sub-basin structures. Where gravity constraints do not exist, we estimate basin depth based on regional averages.

Lateral variations in model boundaries (e.g. Moho depth) and seismic velocity are based on published studies (e.g. Zandt et al., 1995; Mooney, http://quake.wr.usgs.gov/research/structure/CrustalStructure/database/index.html). These profiles and point measurements suggest that the depth to Moho within the Basin and range can vary between 28 and 35 km. Our study extends into the Colorado Plateau and Sierra Nevada Mountains, where the crustal thickness exceeds 40 km. These changes in Moho depth focus and defocus energy and cause considerable variability in regional-phase amplitude (Zandt et al., 1995). Bulk seismic properties also vary within the study area (Mooney, www.quake.wr.usgs.gov/research/structure/CrustStructure/crust), and we include these variations in order to produce the most realistic simulations possible.

Stochastic roughening of boundaries and media

Although we are taking great measures to incorporate as much deterministic structure as possible, it is impossible to construct a model with sufficient detail without a major 3-dimensional imaging campaign. In order to better simulate the earth, we are using geostatistical simulation techniques to perturb geologic boundaries and elastic parameters within geologic units. Statistical characteristics are gleaned from densely sampled data sets, and these characteristics are then used to "roughen" the model in areas with few data constraints.

Figure 3 is an example of a conditional simulation of the upper contact of Paleozoic (Pz) sedimentary rocks near Rainier Mesa. The top of the Pz is one of the first major seismic contrasts encountered by the NPE wavefield. Therefore, proper simulation of this contact is critical for realistic evaluation of seismic scattering. Numerous boreholes and surface exposures define the Pz contact in the southeast portion of the local model. Elsewhere, only the general dip and depth of the Pz contact are constrained. If conventional interpolation is used to construct the Pz surface, then the surface is quite smooth in areas with sparse borehole sampling (Figure 3a,b). Figure 3c,d shows that a more realistic Pz surface can be constructed through conditional simulation. The new surface will scatter high-frequency energy more readily than a smooth surface and may help to explain the frequency dependence of Rg attenuation.

Validation Data

Most of the local and regional recordings of the NPE have been well studied (see NPE volume), and these data were bundled soon after the shot. Stations included in the NPE data bundle are shown in Figure 4a,b. At distances less than a few kilometers, accelerometers were deployed on the surface and in nearby tunnels, providing important constraints on the early development of the wavefield. Many short period instruments were deployed on the surface within 20 km of the shot. These recordings providing further constraint on the early evolution of the wavefield, particularly the evolution of short-period surface waves. LLNL and the University of Arizona broadband deployments cover near-regional distances (out to ~300 km) with linear arrays towards the northwest and east, respectively. These deployments record the complexity of regional wave propagation from the NPE. A number of permanent stations provide further constrain on regional wave propagation.

The University of Nevada, Reno (UNR) recoded the NPE on nearly 50 stations that extend southwest of Rainier Mesa (Smith et al., 2000) (Figure 4c). The UNR data set provides unique coverage in the 6 km to ~100 km distance range. This data set was not included in the NPE data bundle, and it has not been widely distributed. Therefore, we briefly describe the waveform characteristics here. The majority of the instruments deployed were short-period, 3-component seismometers (S-13), and a limited number of broadband instruments were deployed in Death Valley. Most records closer than 16km were clipped, but the previously discussed recordings (from the data bundle) cover that distance range. The UNR recordings contain significant Sg energy between 20 km and 95 km (Figure 5). The distinct Sg energy is consistent with previous observations that suggest generation of S-energy soon after the shot.

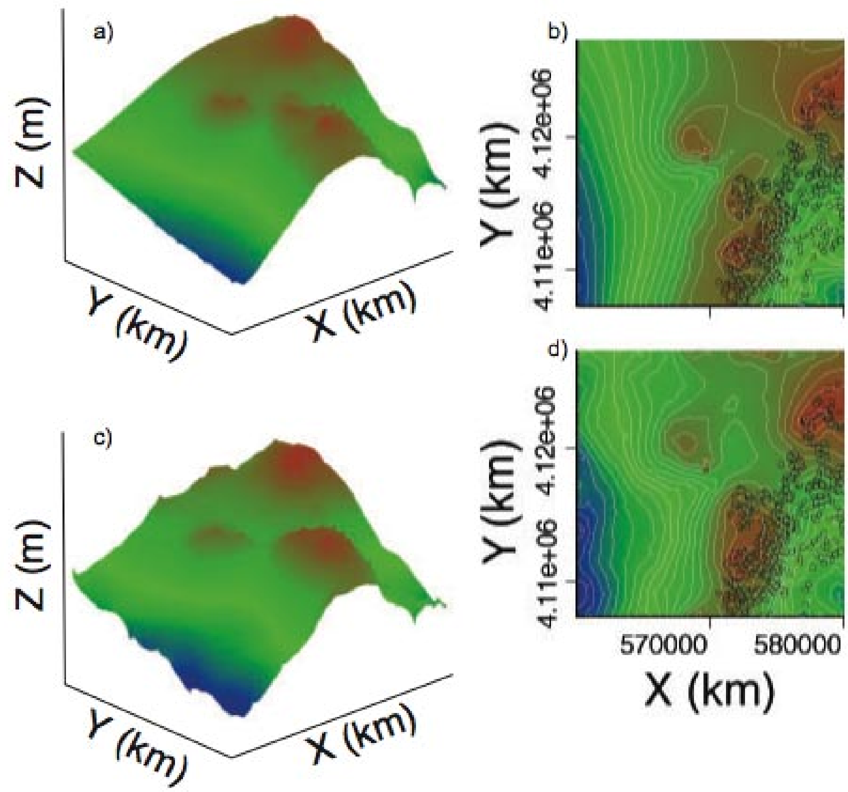

Figure 3. Conditional simulation of the upper contact for Paleozoic (Pz) rocks. a) Surface determined using borehole data, which are concentrated in the southeast portion of the model area, and a simple interpolation algorithm. b) plan view of a) showing borehole data (circles colored in accordance with borehole observation). Note the difference in the roughness of the surface between areas with and without borehole data. c) Conditional simulation of upper Pz surface using statistical characterization of surface roughness and constraints from borehole observations. d) Plan view of c) showing borehole observations and consistent surface roughness in areas with and without observations.

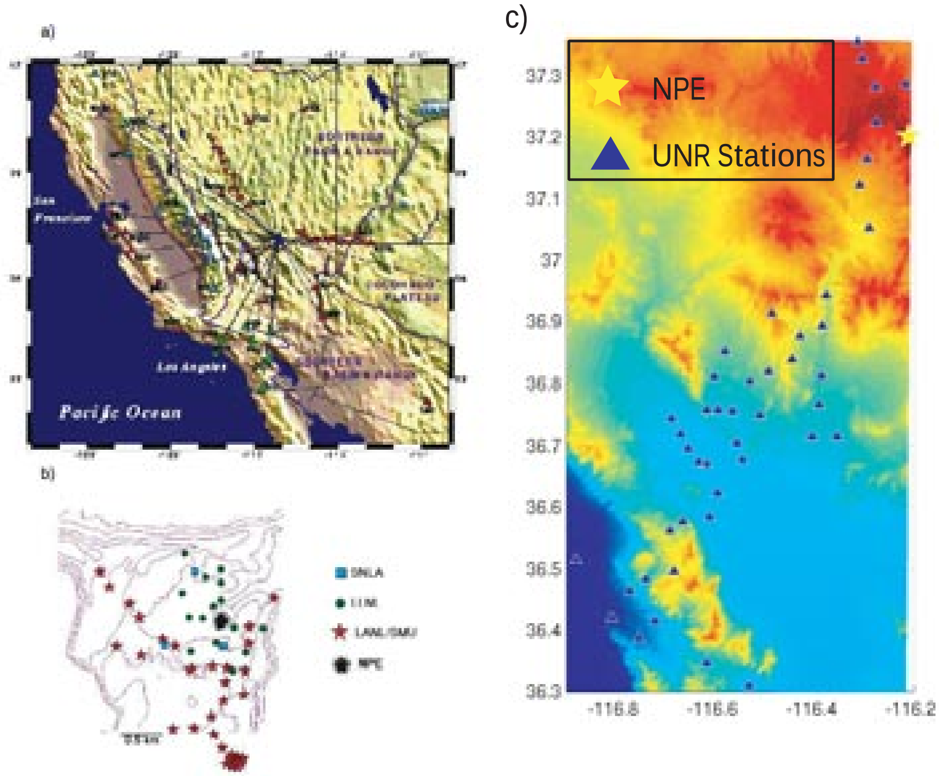

Figure 4. a) Regional and b) local networks recording the NPE shot. c) UNR stations provide unique distance and azimuth coverage. The local and regional recordings of the NPE provide validation data for simulations.

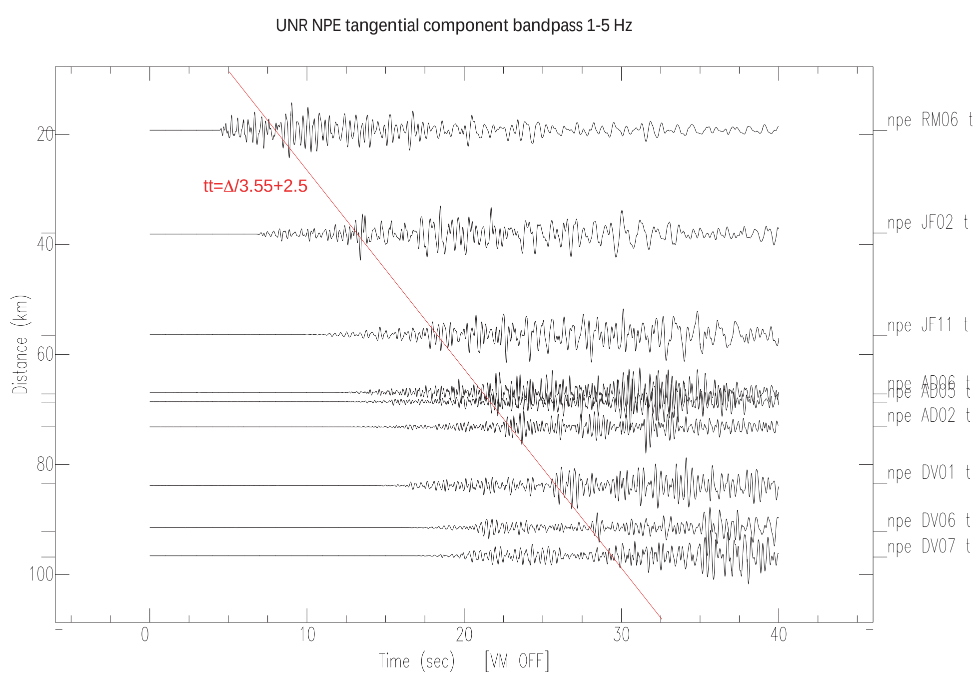

Figure 5: Development of Sg is documented on tangential recording of the NPE on the UNR stations. Sg velocity is consistent with basin and range models, but the arrival is delayed by ~ 2.5 seconds.

Seismic Simulation

E3D Finite-Difference computer code

We are beginning to run simulations with early versions of our geologic model. The simulations are performed with E3D, a state-of-the-art finite-difference seismic wave propagation code developed at LLNL (e.g., Larsen and Schultz,1995; Larsen and Grieger, 1998). A preliminary simulation along the University of Arizona line is shown in Figure 6. Model grid spacing for this simulation is 40m. Incorporation of Moho topography and a crude estimate of topography produce considerable S-energy (green). The snap shot is taken at approximately 9 seconds after shot detonation, when Pn is emerging as the first arrival

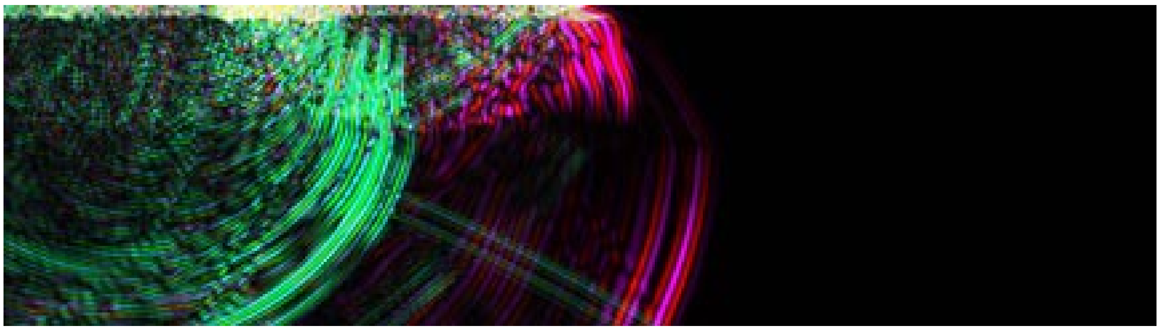

Figure 6. Snap shot of a preliminary NPE simulation. This simulation is 300km in length and 80 km in depth. P-wave energy is shown in red, and S_save energy is shown in green.

Validation of a simulation along the LLNL line is shown in Figures 7 and 8 (from Preston et al., 2004). The simulation includes topography, preliminary basin models, and Q. Model grid spacing in this instance is 250m, enabling simulation at periods greater than 1 second. Figure 7 shows Pn and Pg phases at station BHR5 (LLNL line). Travel-times for Pn and Pg are well predicted, and initial (first swing) amplitudes are also in approximate agreement with the simulations. However, figures 7 and 8 show that Pg complexity is not well predicted. Figure 8 shows that Lg is produced in the simulation and the arrival time is in reasonable agreement with the validation data. However, Lg amplitudes are severely under predicted. While Lg amplitudes are under predicted, the simulations contain large surface waves that are not present in the data. Our preliminary models contain minimal complexity, and we believe that agreement between simulations and the validation data set will improve as model complexity is added.

CONCLUSIONS AND RECOMMENDATIONS

We review the first year of progress on the SIRES project. During this period we made use of geologic and geophysical studies at NTS to construct a detailed earth model within 10km of the NPE shot. Geologic and geophysical studies are being used to construct a regional model out to several hundred kilometers from the NPE. Further, we are incorporating geostatistical simulation to perturb geologic contacts and elastic parameters within geologic units to made the model as realistic as possible.

We have compiled all regional recordings of the NPE, including a temporary UNR deployment that has not been widely distributed. The UNR data set provides unique distance coverage in the range from 6 km to approximately 100 km,. In the UNR data set, the Sg phase is evident from 10 km to 100 km (closer seismograms are clipped in this data set), but the arrivals are delayed by ~2.5 seconds from predictions. These observations are consistent with previous observations, which have been interpreted as resulting from conversion of Rg to higher-mode S-energy at some distance from the source.

We are nearing finalization of the NPE local model. Construction of the regional model is well underway and we are starting to conduct simulations to test the effect of topography, basins, Moho topography, and lateral variations in velocity structure. Although simulations to date are preliminary in nature, we are finding that model heterogeneity is crucial for simulating the complexity of regional seismograms. Other important findings are as follows:

- Relatively simple models predict Pn and Pg travel-times
- Inclusion of topography, basins, and Q reasonably predicts first-swing amplitudes for Pn and Pg.
- Complexity of Pg is not well simulated with the current model.
- A model with topography, basins and Q produces an Lg phase with arrival-times that are in good agreement with the validation data.
- Simulated Lg amplitudes are far smaller than observed, but we note that this simulation does not include the complex local model.

Our next step is to conduct 3-dimensional simulations using our detailed local model and to validate these simulations with the local data set. We will continue to compile geologic and geophysical studies to complete the regional model. After the local model is imbedded in the regional model, we will test the model via regional 2-dimensional simulations. The project will culminate in a tera-scale, 3-dimensional simulation.

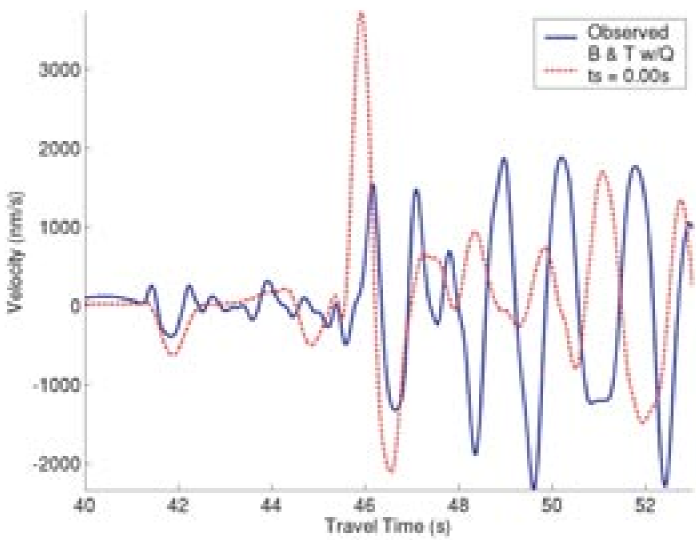

Figure 6. Simulation of station BHR5 on the LLNL line. Simulation includes topography, basins, and Q. Pn and Pg timing and the first swings are well characterized.

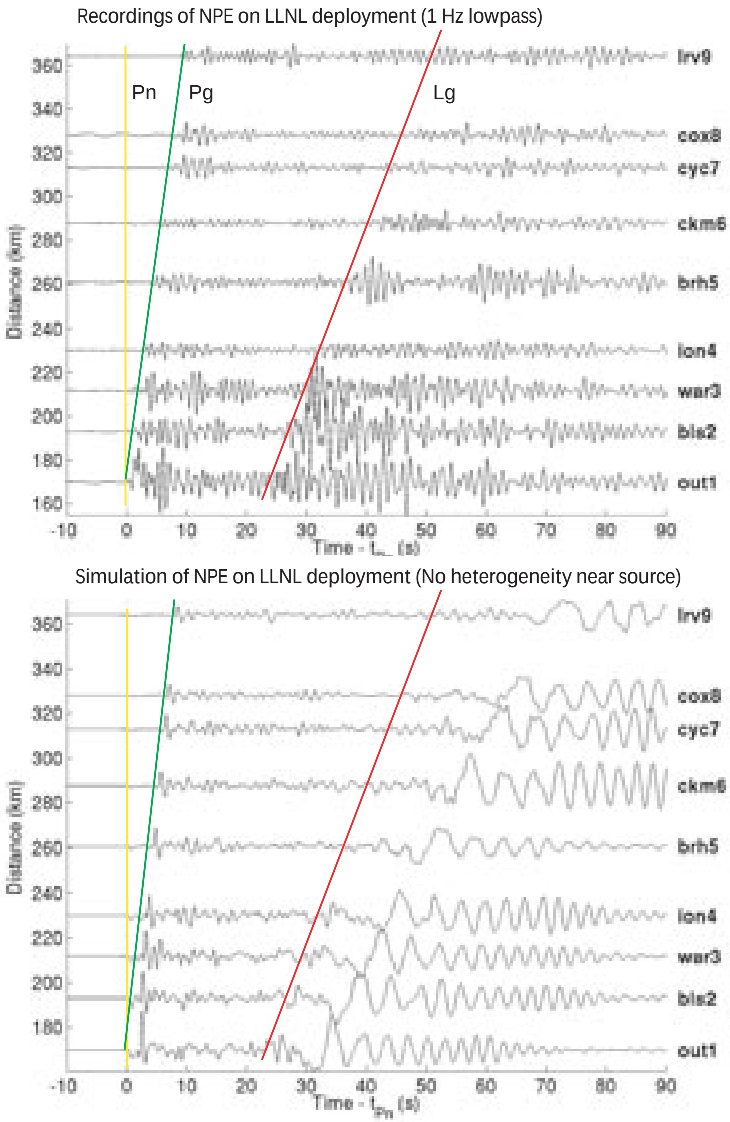

Figure 7. Observations (above) of NPE observed along LLNL (northwest) line. Two-dimensional NPE simulation along LLNL line. Simulations includes topography, basins and Q. Simulations of Pn, Pg, and Lg arrival times are good. Pn is well characterized. Pg complexity not predicted, and the amplitude and complexity of Lg are not predicted. Surface waves are predicted but not observed.

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